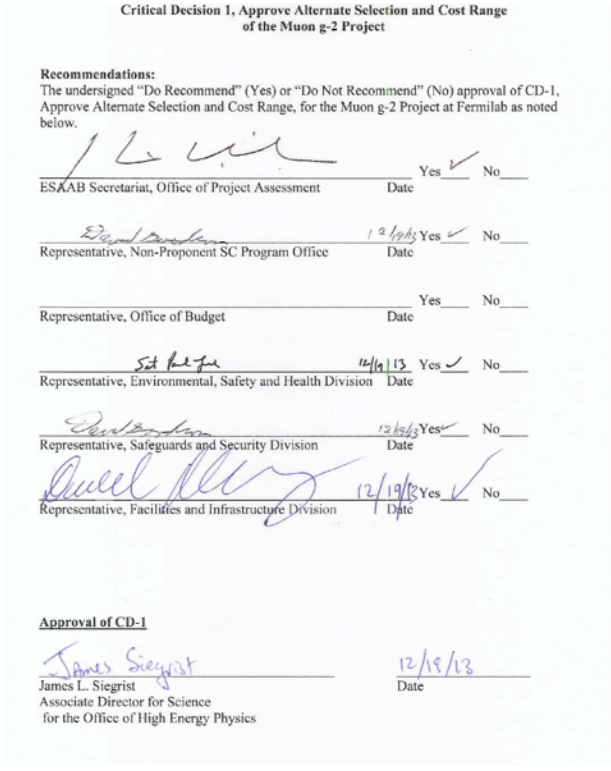
Muon $(g-2)$ to $\leq$ 0.14 ppm

David Hertzog and Lee Roberts
for the E989 Muon $(g-2)$ Collaboration

E989 Timeline

- March 2009 – Proposal presented to PAC
  - What's the real cost?
- May 2009 Cost review by Ron Ray Committee
- November 2009 – Update to PAC
  - "Experiment meets the criteria for Stage 1 approval … recommends that the Laboratory clarify with the DOE the prospects for obtaining support for P-989"
- January 2011 – Stage 1 approval
- September 2012 – CD-0 granted
- June - 20 July 2013 – 14 m diameter coils moved to Fermilab
- September 2013 – CD-1 review
- December 2013 CD-1 approved



Critical Decision 1, Approve Alternate Selection and Cost Range of the Muon g-2 Project

Recommendations:
The undersigned "Do Recommend" (Yes) or "Do Not Recommend" (No) approval of CD-1, Approve Alternate Selection and Cost Range, for the Muon g-2 Project at Fermilab as noted below.

ESAAB Secretariat, Office of Project Assessment — Date — Yes ✓ No

Representative, Non-Proponent SC Program Office — 12/19/13 — Yes ✓ No

Representative, Office of Budget — Date — Yes No

Representative, Environmental, Safety and Health Division — 12/19/13 — Yes ✓ No

Representative, Safeguards and Security Division — 12/19/13 — Yes ✓ No

Representative, Facilities and Infrastructure Division — 12/19/13 — Yes ✓ No

Approval of CD-1

James L. Siegrist
Associate Director for Science
for the Office of High Energy Physics
12/19/13 Date

Construction Funds (not ops)

Source	$ M	Comment
DOE OHEP	46.4	**CD-1 guidance**; $9 M obligated; **$12 M contingency on remaining (40%)**
DOE Early Career	0.5	Casey: trackers ($2.5 M award)
NSF MRI	3.6	Consortium Proposal; Detectors; Electronics, DAQ, Including 30% match (mostly from Universities)
ITALY: INFN	0.40**	Laser calibration
UK: STFC	0.40	Trackers
China: Shanghai	0.25	PbF2 crystals *
Texas Instruments	0.20	Digitizer chips*

Awarded

Additionally **E821 Components And most of the Pbar Complex**	**50 – 100 M (re-used equipment)**	**Storage Ring, Vacuum, Power supplies, Pbar (now muon) target system, Beamline elements, … Debuncher, etc etc,**

***part of MRI match formula **$136k awarded, remainder subject to 1st year success**

E989 Collaboration: 38 Institutes; >150 Members

Domestic Universities

- Boston
- Cornell
- Illinois
- James Madison
- Massachusetts
- Mississippi
- Kentucky
- Michigan
- Michigan State
- Mississippi
- Northern Illinois University
- Northwestern
- Regis
- Virginia
- Washington
- York College

- **National Labs**
  - Argonne
  - Brookhaven
  - Fermilab
- **Consultants**
  - Muons, Inc.

Italy

- Frascati,
- Roma 2,
- Udine
- Pisa
- Naples
- Trieste

China:

- Shanghai

The Netherlands:

- Groningen

Germany:

- Dresden

Japan:

- Osaka

Russia:

- Dubna
- PNPI
- Novosibirsk

England

University College London

Liverpool

Oxford

Rutherford Lab

Korea

KAIST

FTE Committed

Survey of Collaboration for P5

Construction	Runnning	Analysis
2014 - 2016	2017-2018	2019 - 2022
91	80	68

Co-spokespersons: David Hertzog, Lee Roberts

Project Manager: Chris Polly

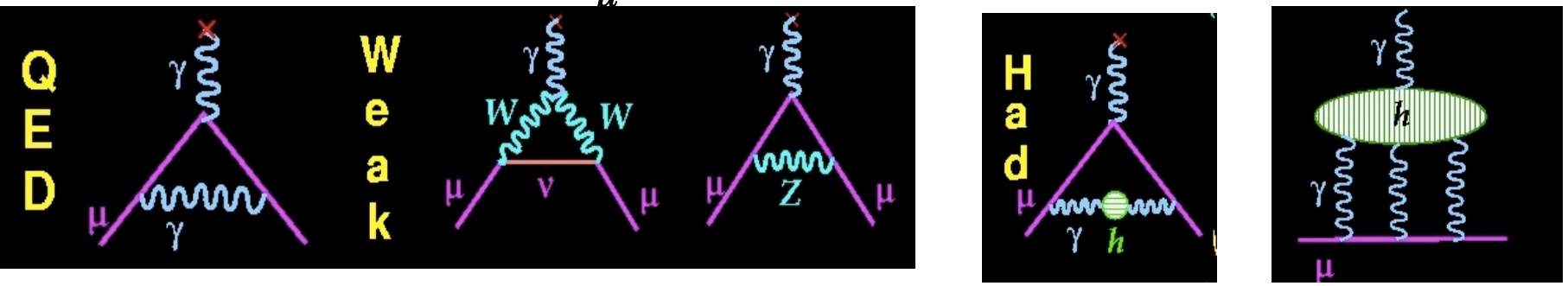
The Muon Magnetic Dipole Moment

$$\vec{\mu} = g\left(\frac{Qe}{2m}\right)\vec{s}$$

$$g = 2(1 + a)$$

$$a = \frac{(g-2)}{2}$$

The SM Value for a_μ from $e^+e^- \rightarrow$ *hadrons*

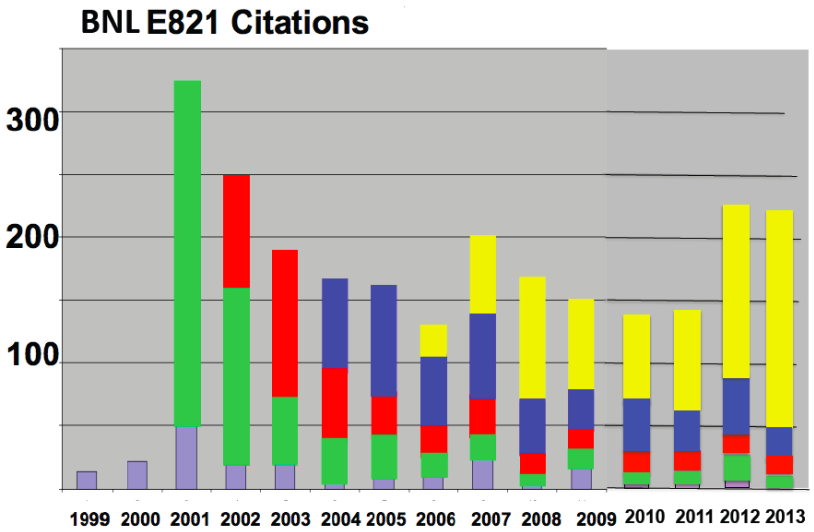


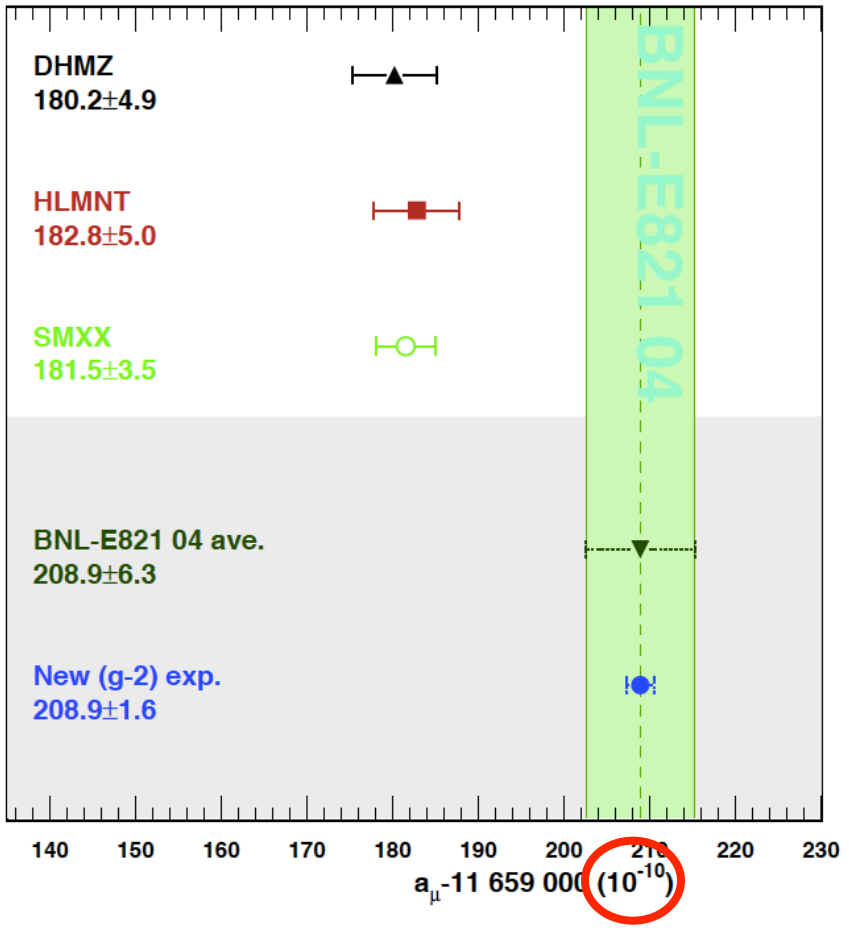
well known **significant work ongoing**

	Value $(\times 10^{-11})$ units
QED $(\gamma + \ell)$	$116\,584\,718.951 \pm 0.009 \pm 0.019 \pm 0.007 \pm 0.077_{\alpha}$
HVP(lo) [20]	$6\,923 \pm 42$
HVP(lo) [21]	$6\,949 \pm 43$
HVP(ho) [21]	-98.4 ± 0.7
HLbL	105 ± 26
EW	154 ± 1
Total SM [20]	$116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}} (\pm 49_{\text{tot}})$
Total SM [21]	$116\,591\,828 \pm 43_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}} (\pm 50_{\text{tot}})$

For details see: arXiv:1311.2198v1 [hep-ph] 9 Nov 2013

The Physics Interest Remains Large





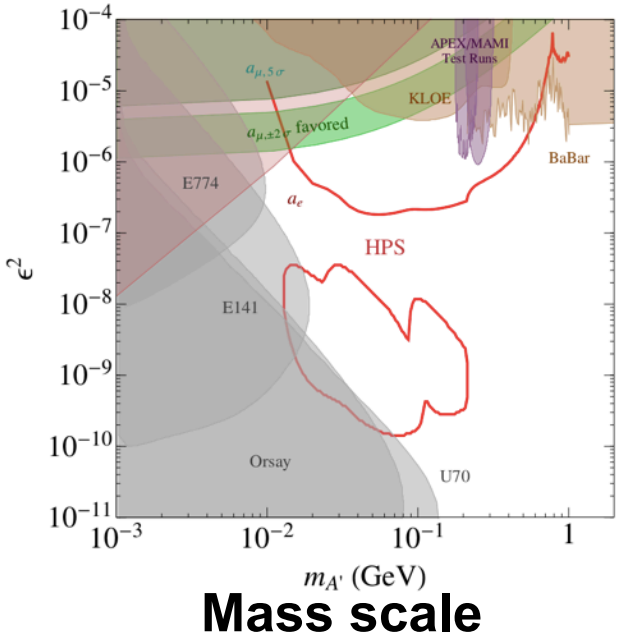
With the Higgs discovery, there has been increased interest in our E821 result.

Carey, et al., PRL 82, 1632 (1999)
Brown, et al. PRD 62, 091101 (2000)
Brown, et al. PRL 86, 2227 (2001)
Bennett, et al. PRL 89, 101804 (2002)
Bennett, et al. PRL 92, 161802 (2004)
Bennett, et al, PRD 73, 072003 (2006)

$$\Delta a_\mu^{(\text{today})} = (287 \pm 80) \times 10^{-11}$$

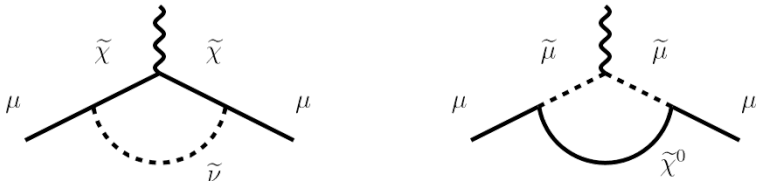
New physics enters through loops. What might the g-2 signal imply?

- Dark Photons
  - light new vector particles V kinetically mixed with the photon



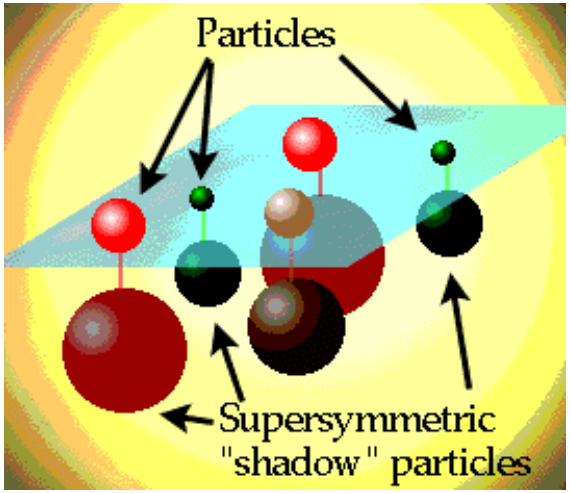
Mass scale

- Supersymmetry



$$a_\mu^{\mathrm{SUSY}} \simeq (\mathrm{sgn}\mu)\, 130\times 10^{-11} \tan\beta \left(\frac{100\ \mathrm{GeV}}{\tilde{m}}\right)^2$$

Difficult to measure at the LHC



- The Uninvented
  - Perhaps the most important of all

The Experiment in a nutshell

- Use the Fermilab accelerator complex to deliver a pure 3.09 GeV/c muon beam.
- Store the beam in a precision magnetic storage ring with electric quadrupoles and measure $\omega_a = \omega_S - \omega_C$, the rate that the spin turns relative to the momentum

$$\vec{\omega}_a = -\frac{Qe}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

0

$\gamma_{magic} = 29.3$

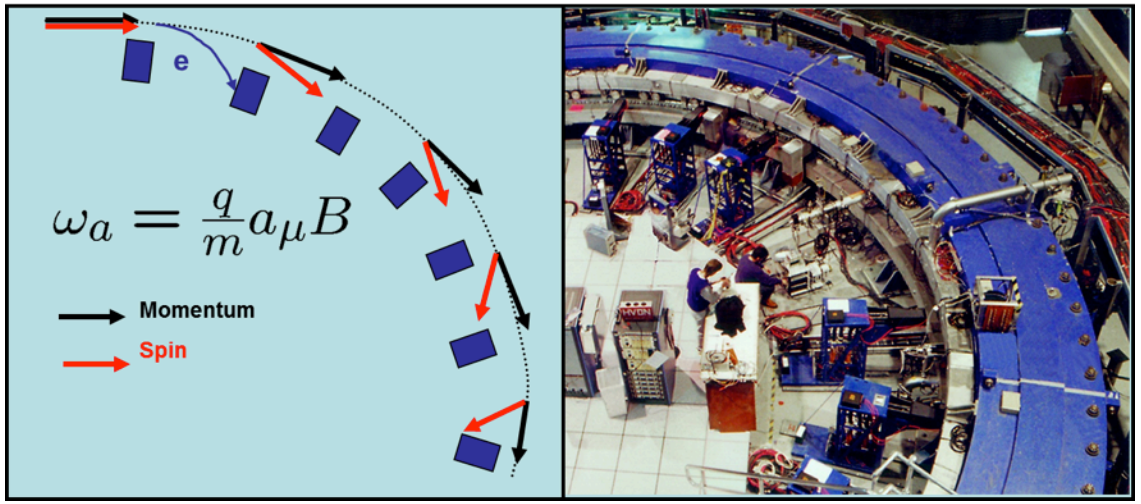
$p_{magic} = 3.09\ \text{GeV/c}$

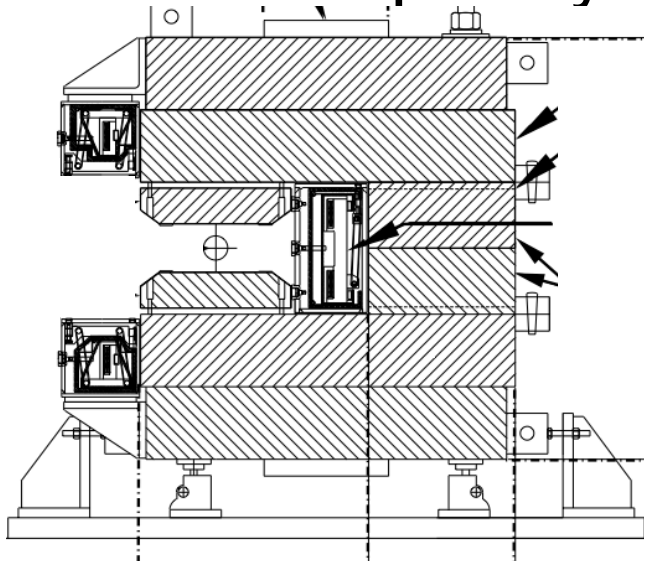
Because $g > 2$, $(a \neq 0)$; the spin gets ahead of the momentum

- Measure ω_a and B
  (calibrated to the Larmor frequency of a free proton ω_p).

Measurement of ω_a and $\langle B \rangle$ (ω_p)

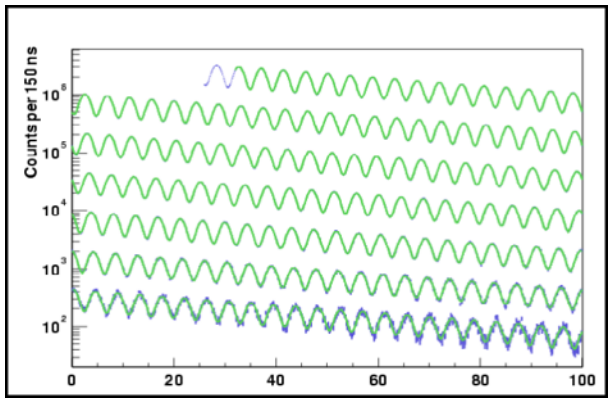
Systematic error budget is 70 ppb for each frequency.





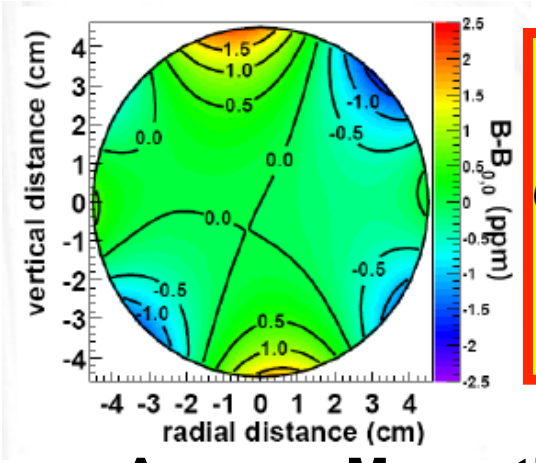
$$\vec{\omega}_a = \omega_S - \omega_C = -\frac{Qe}{m} a_\mu \langle \vec{B} \rangle$$

ω_a



ω_p

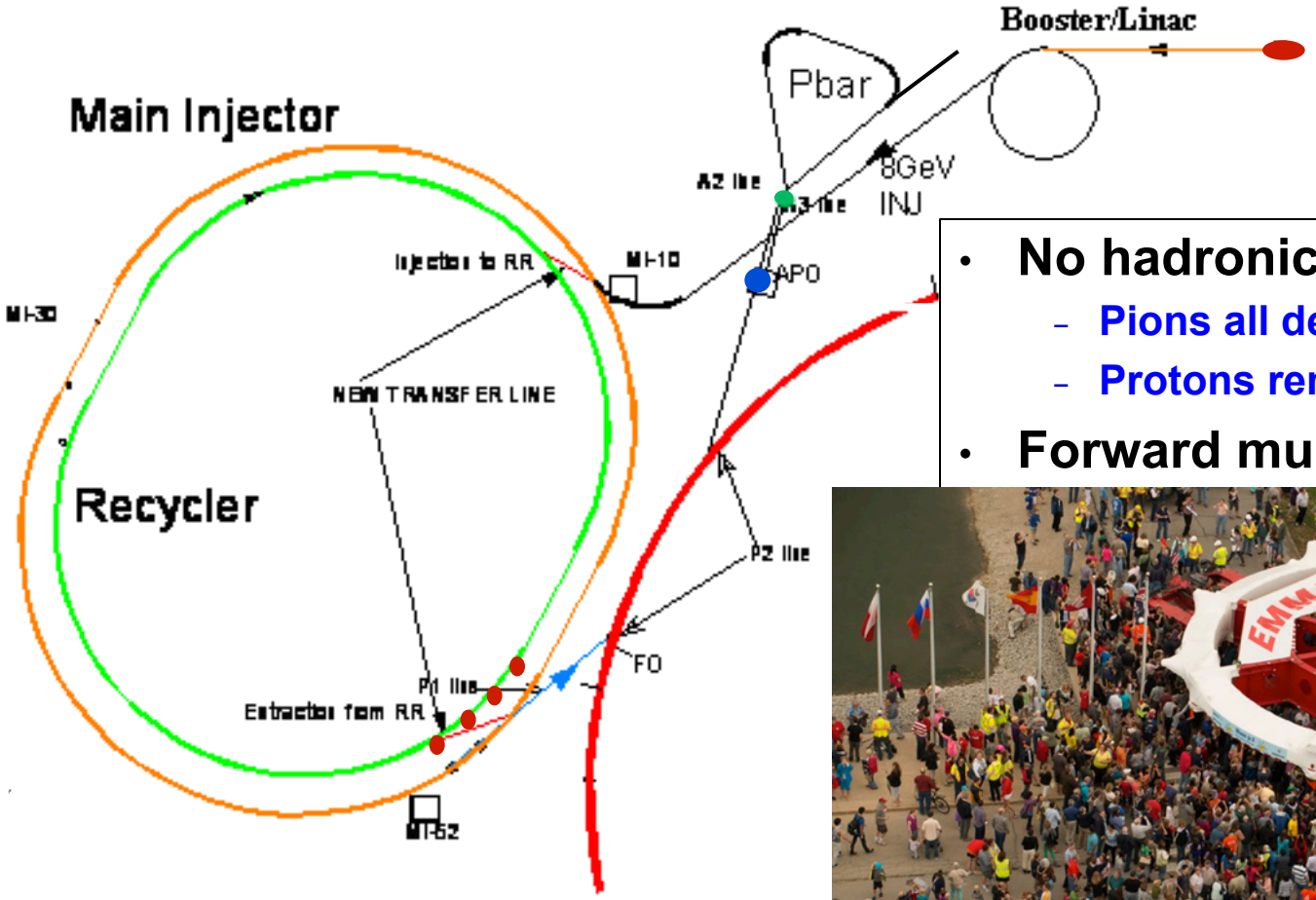
Precession frequency

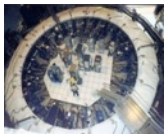


Average Magnetic Field

$$a_\mu = \frac{\frac{\omega_a}{\omega_p}}{\frac{\mu_\mu}{\mu_p} - \frac{\omega_a}{\omega_p}}$$

The Beam Plan in a nutshell





- **No hadronic flash**
  - **Pions all decay**
  - **Protons removed by a kicker**
- **Forward muons collected**

Coils arrives at FNAL

Improvements to reach the precision: ± 0.14 ppm

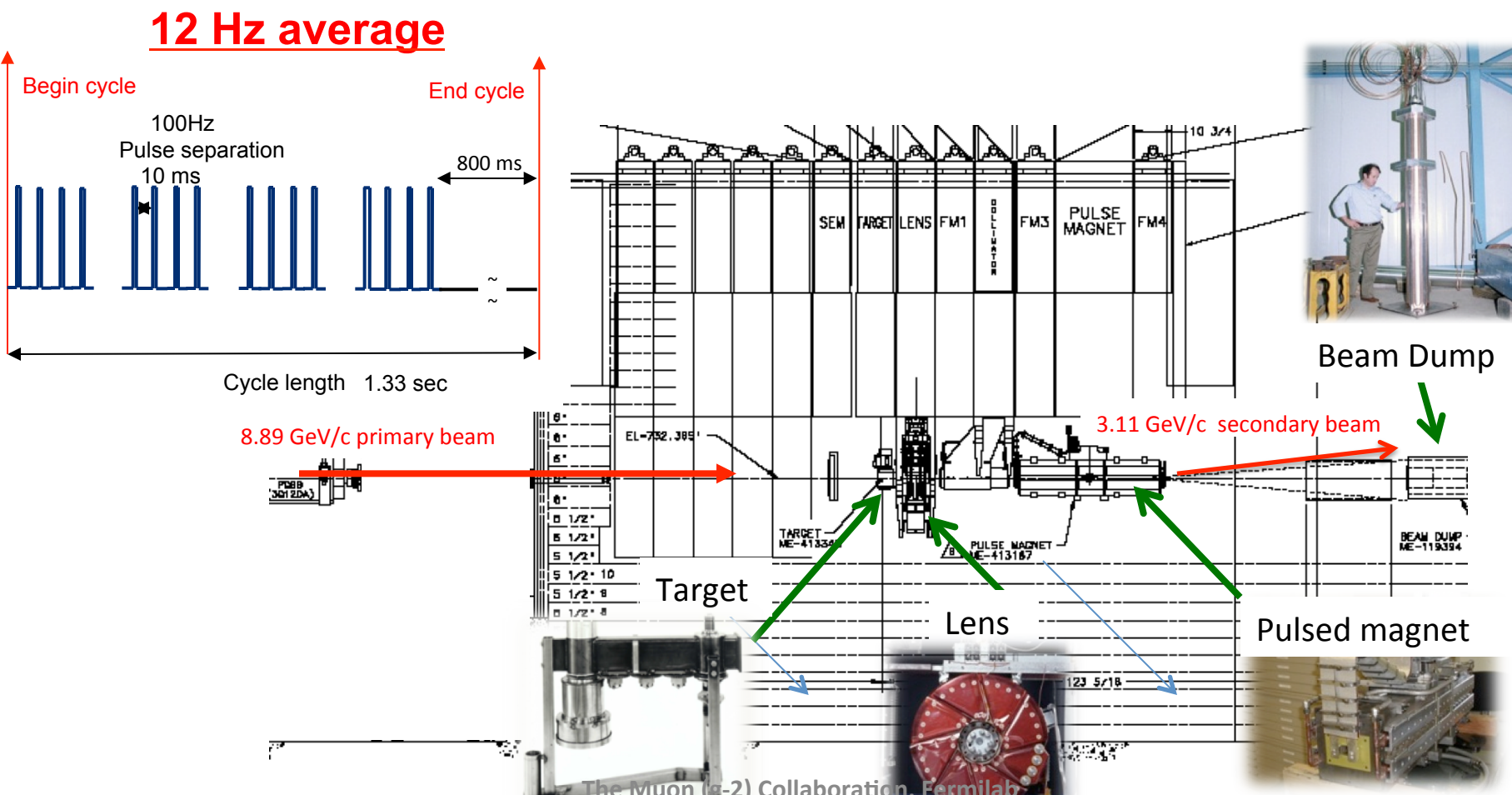
- Statistics (× 21 over E821)
  - **More Muons** – Need ~ 2 × 10^{11} measured decays
    - muons delivered more often into the ring
    - Improved Muon **Storage Fraction**
- Systematics (× 3 improvement over E821 → 70 ppb)
  - Reduce ω_a , ω_p **systematic errors**
  - Better **Modeling** of stored beam dynamics
  - Higher **Magnetic Field Uniformity**
  - More precise B-Field **Monitoring and Calibration**

Technical Progress

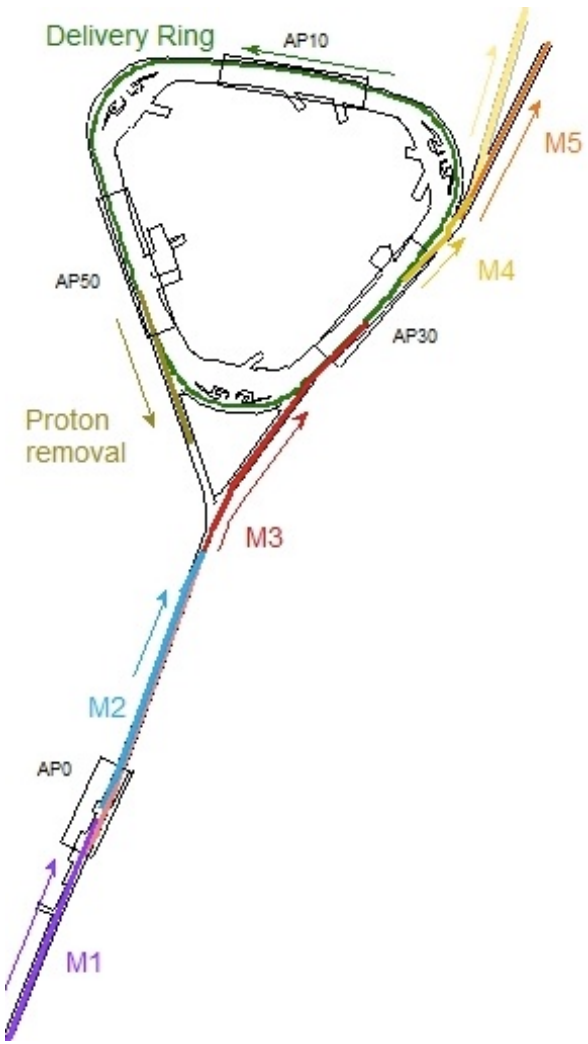
An incomplete parade of progress on all fronts

p-bar Target Station will be reused along with the Lithium Lens.

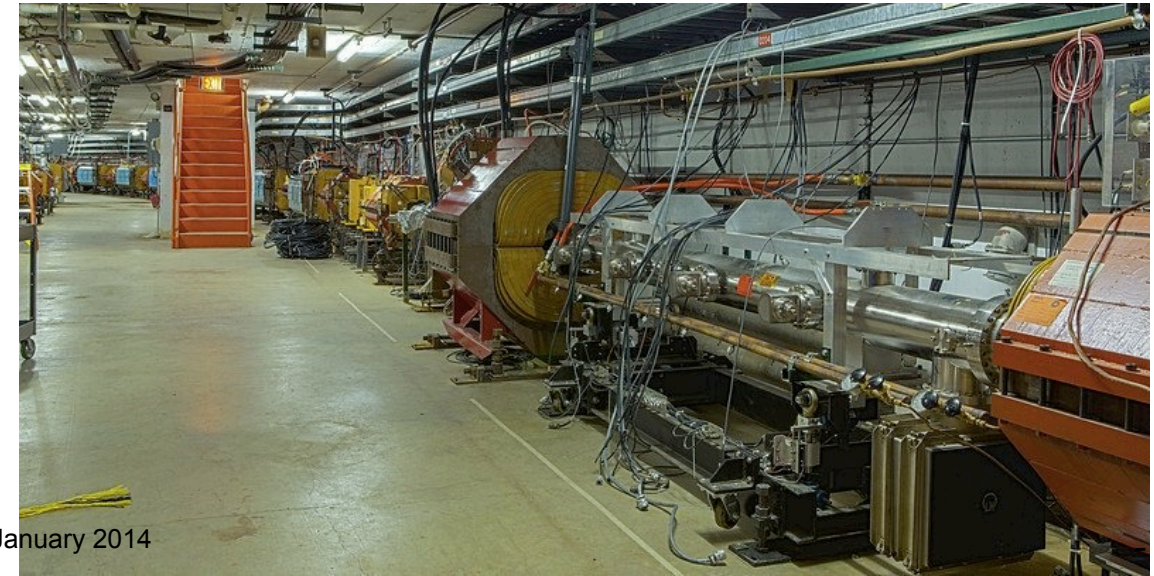
- Working on design of power supplies and beam dump



Beamlines

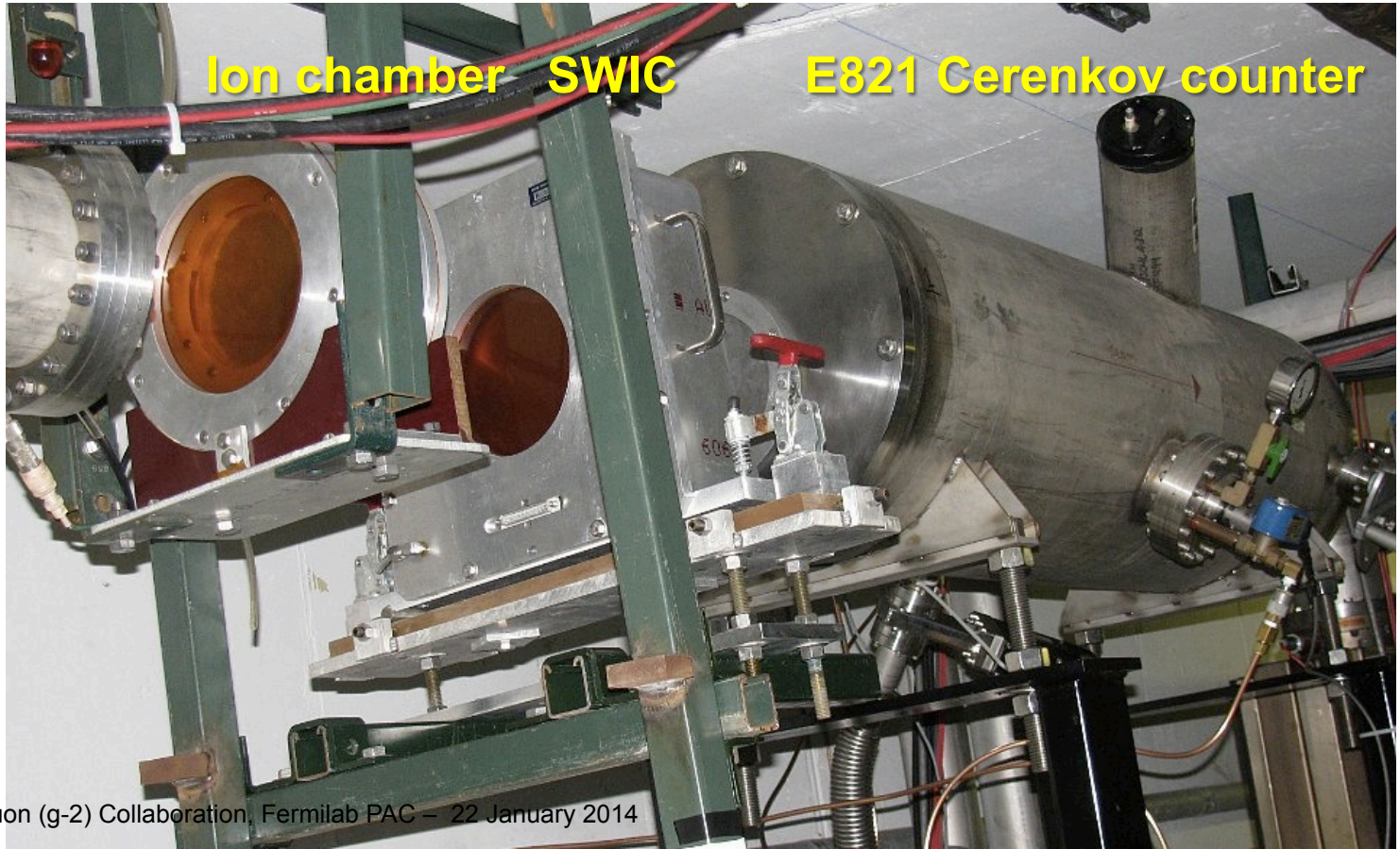


- Re-use existing Antiproton-source infrastructure
- Modify final focus on target for 8-GeV primary beam (M1)
- Improve acceptance / decay-muon capture in secondary lines (M2/M3)
- Reconfiguration of extraction region (D30 straight) and extraction from Delivery Ring
- New external beamline to g-2 storage ring (M4/M5)

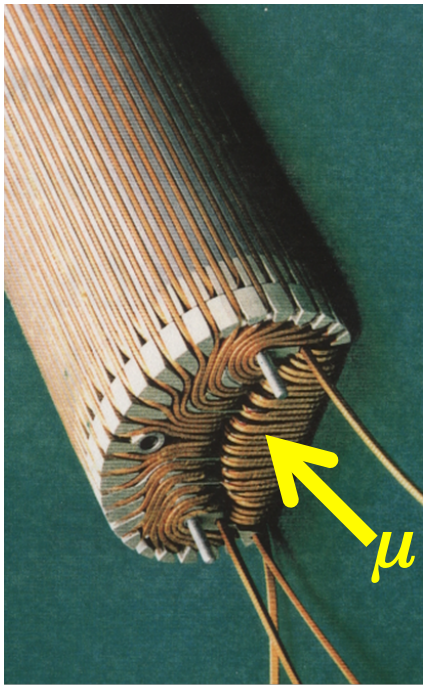


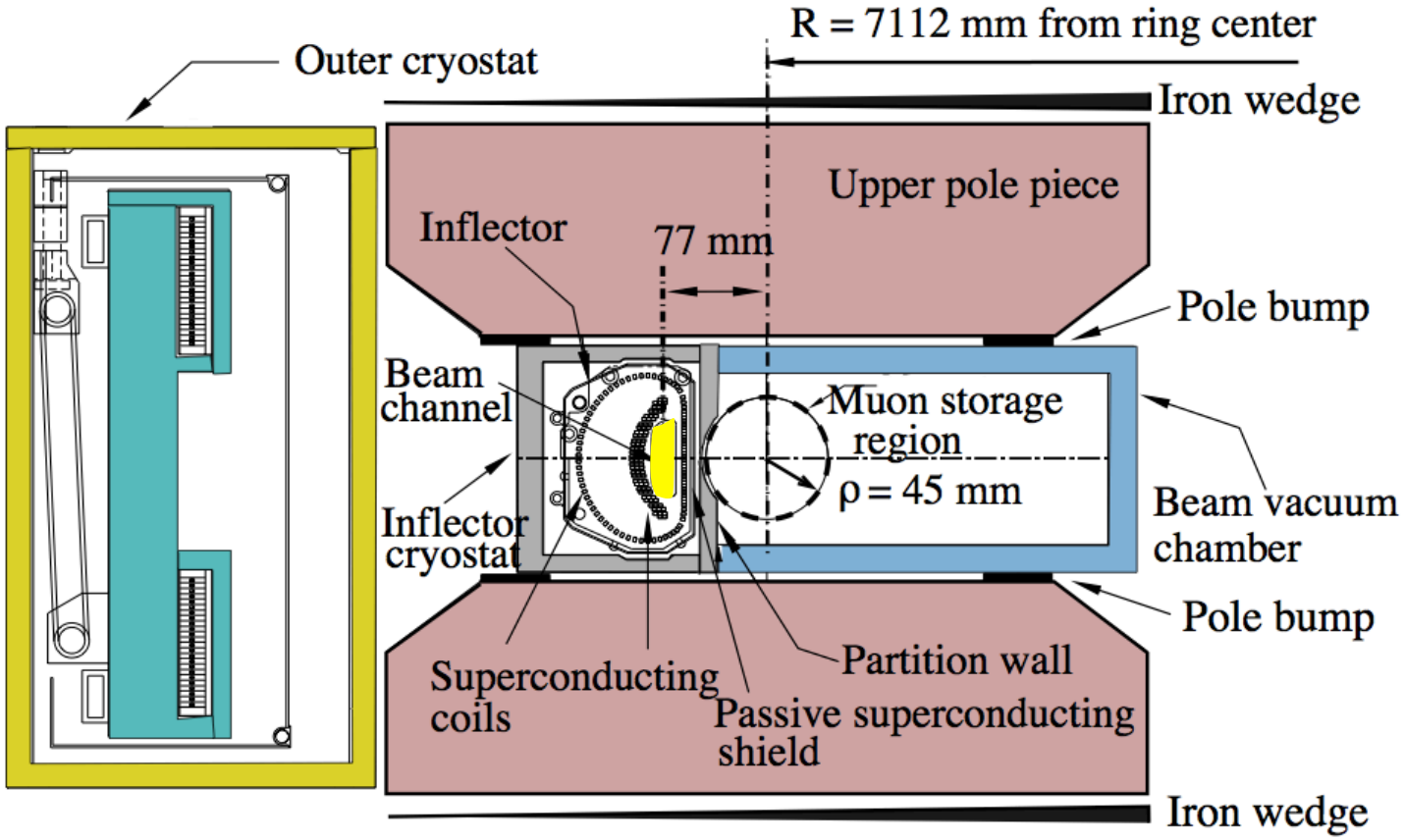
Measuring particle yield at 3.09 GeV/c

- Beam tests in progress to confirm earlier target-yield measurements, look at particle type using Cerenkov counter, and test prototype beam instrumentation. Our collaborator Breese Quinn is working with AD on this.



New Superconducting Inflector to replace E821



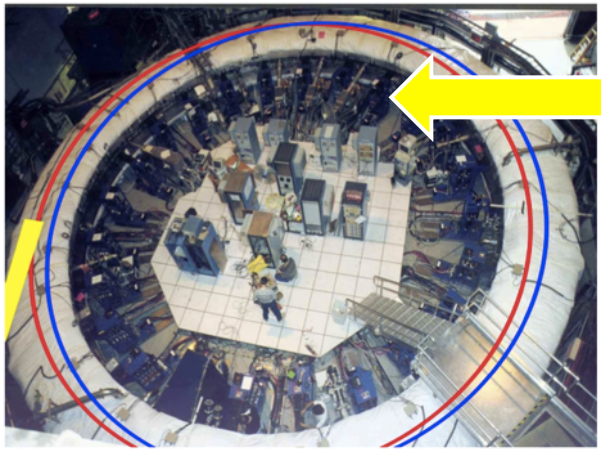


Goal: New inflector with no material over the beam and wider aperture

New Inflector Task Force (Boston, BNL, Cornell, Fermilab, KAIST, RAL)

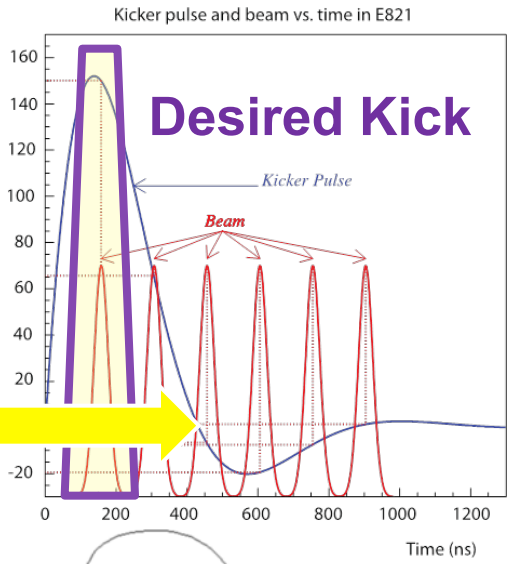
Victoria Bayliss, Tom Bradshaw, Nathan Froemming, Thomas Gadfort, Carol Johnstone, Vladimir Kashikhin, William Morse, Hogan Nguyen, Brett Parker, Chris Polly, Lee Roberts, David Rubin, Yannis Semertzidis, Vladimir Tishchenko, Alexander Zlobin

Improved muon Storage Fraction (Kicker, Quads and Inflector Upgrades)

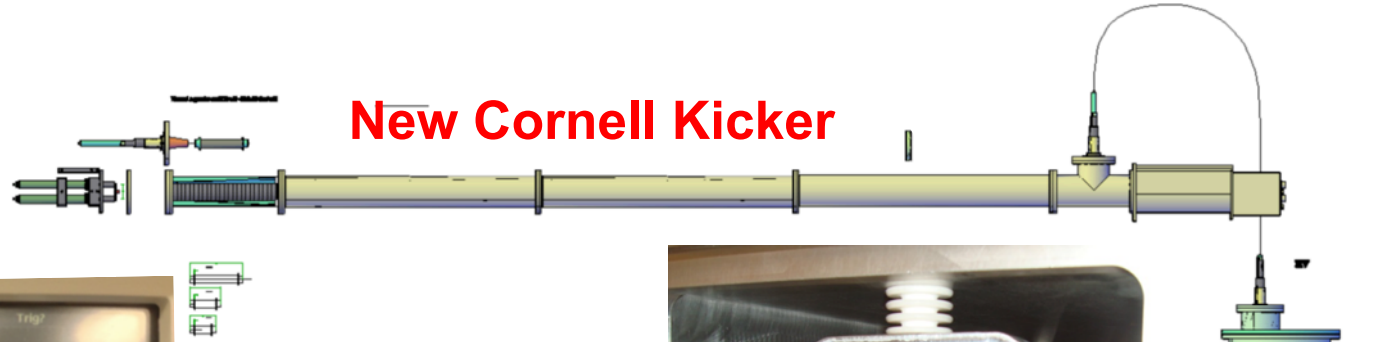


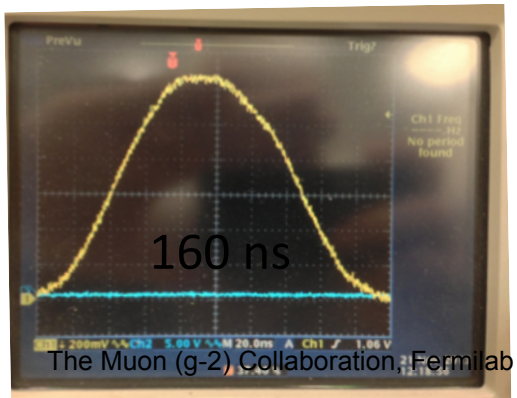
Kicker needed to put Muons onto a Stable Orbit

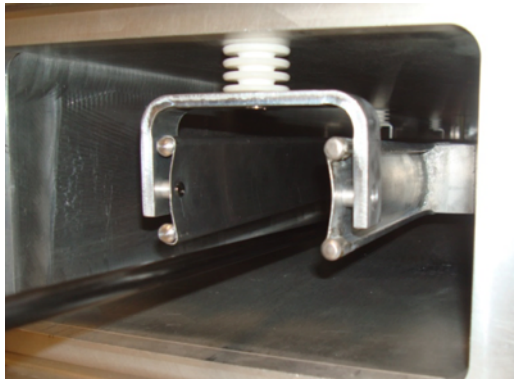
Old kick was too long, and not strong enough



New Cornell Kicker

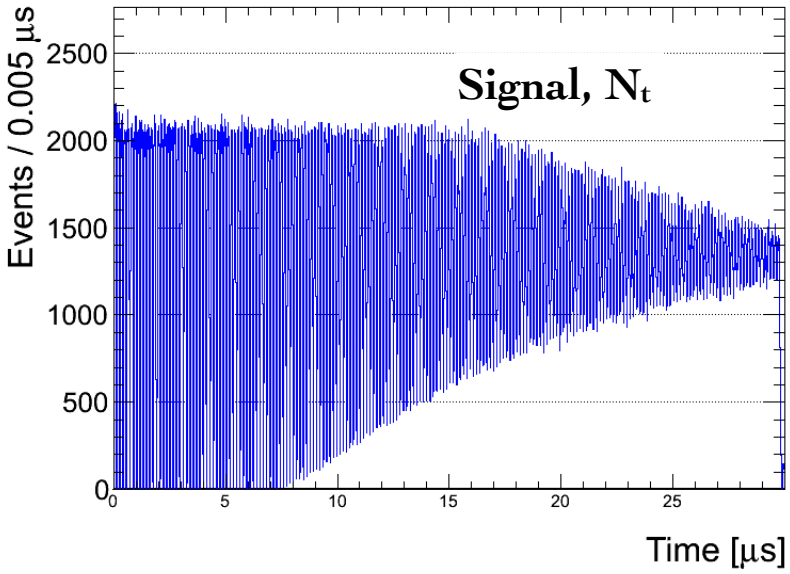


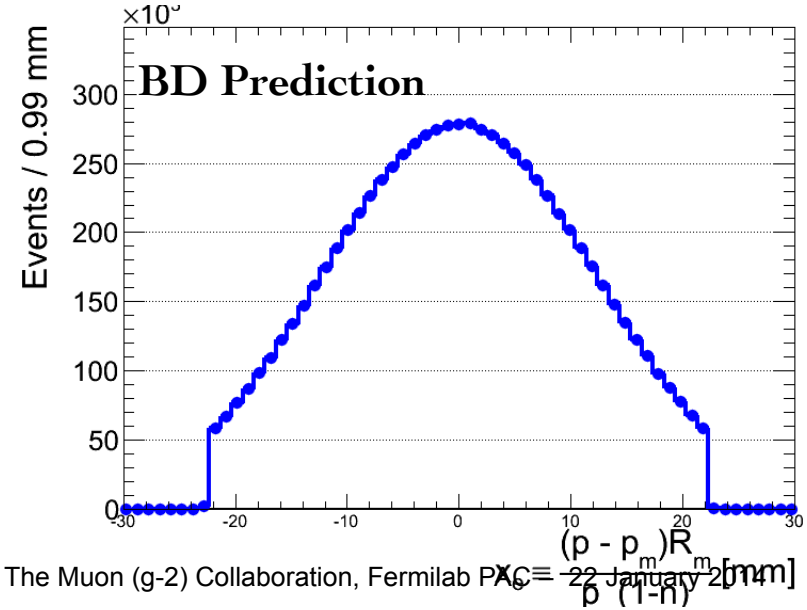




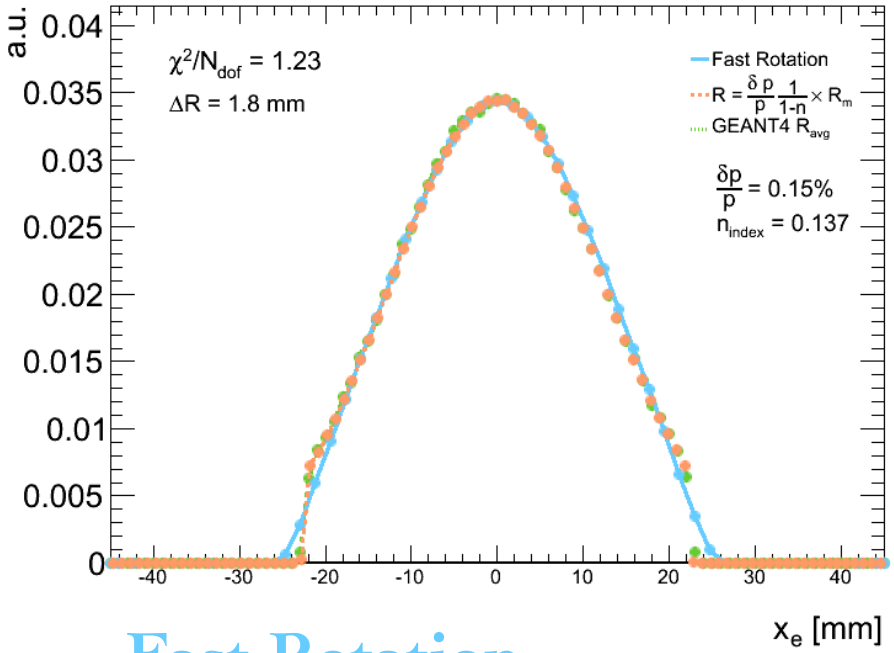
Sophisticated Modeling of beam, ring, decays in the ART framework

- Example: Incoming bunched beam spreading and yielding radial distribution





Distribution of equilibrium radii

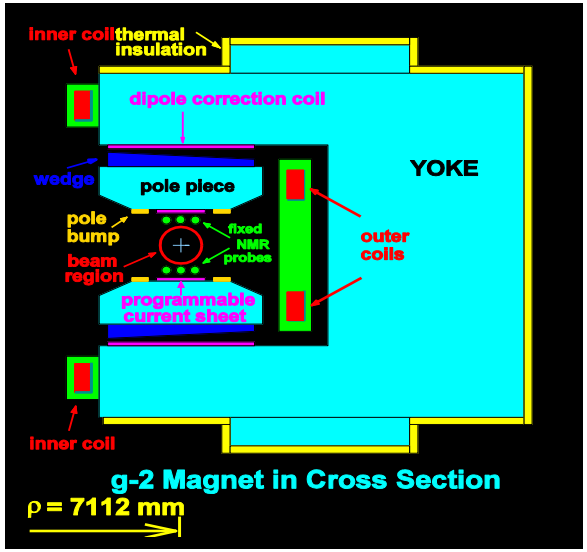


Fast Rotation

BD Prediction

Brute Force GEANT

Higher (field) Uniformity: OPERA 3D and refined shimming tools predict improved intrinsic uniformity



Plus:

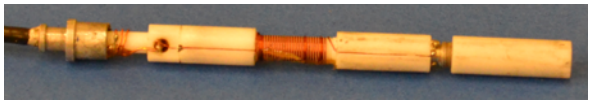
- Strict temperature stability of building
- Stable floor in the experimental hall
- Triple # of useful fixed NMR probes

NMR magnet to be acquired from U. Minn. for precision field work.

- Erik Ramberg in now in charge of acquisition and setting it up at Fermilab
- This is the highest priority of the magnetic field team.

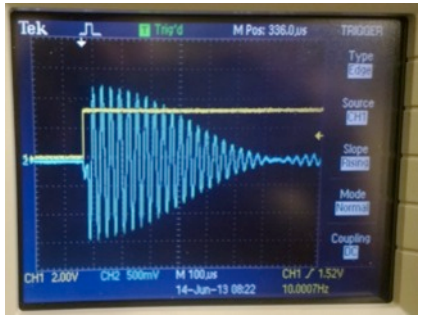
New 1.45T magnet facility at UW to test NMR Probes and Electronics

Probe inventory being tested

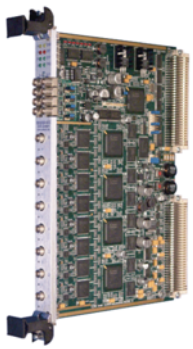


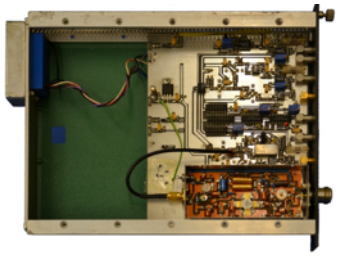
Triage and Repairs of Fixed Probes

1.45 T CENPA test magnet



Proton Free Induction Decay

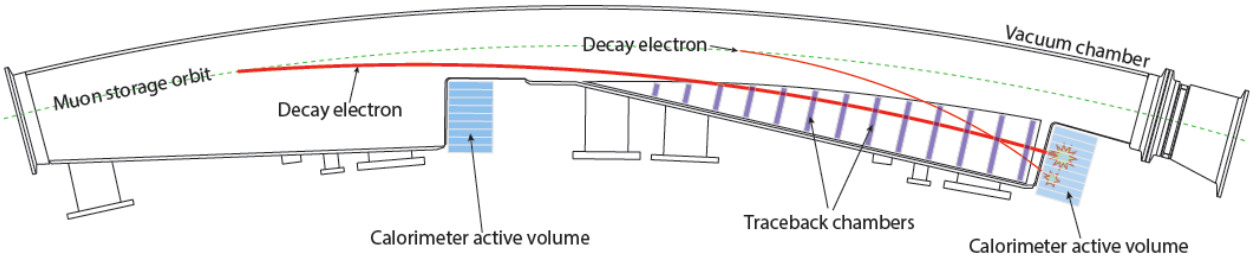




Electronics to be refurbished, rebuilt or replaced

Reduced Precession Systematics:

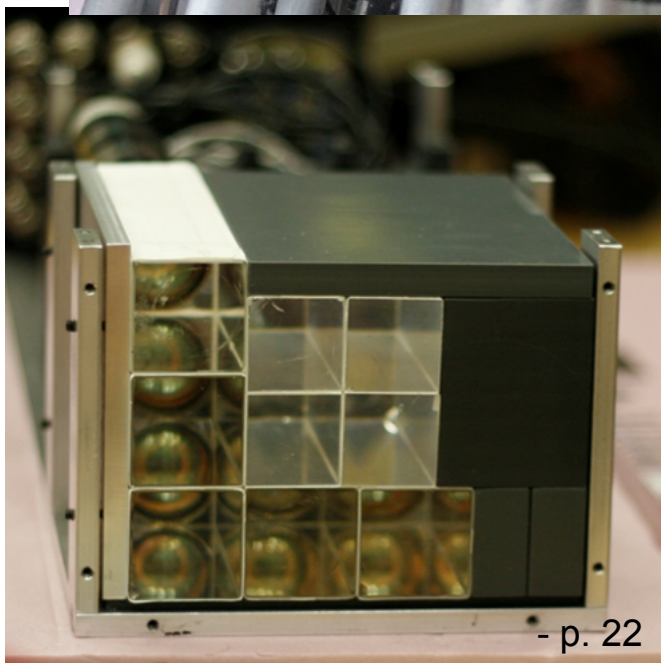
All new detectors, electronics & DAQ



At the SLAC test beam

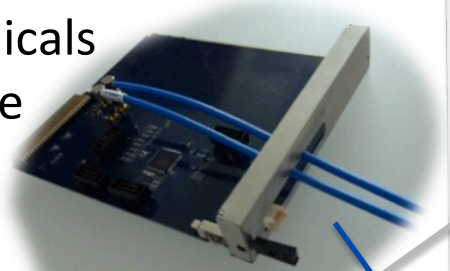
Single particle beam 2.0 - 4.5 GeV
9 crystals, 5 PMTs, 4 SiPMs

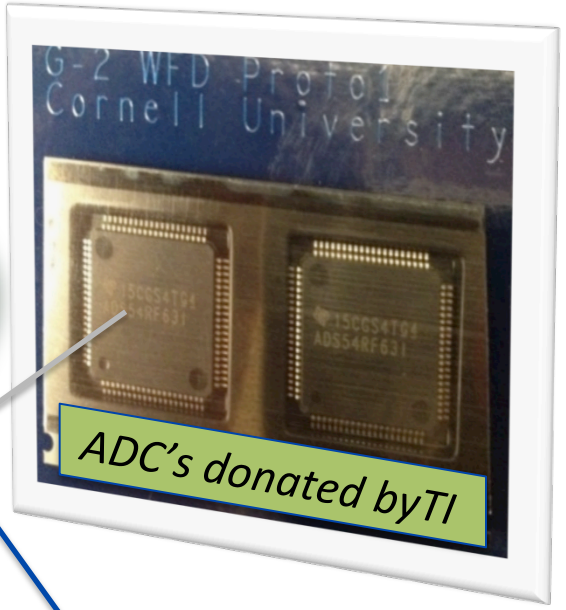
Good energy resolution ~1 pe/MeV.
Excellent energy linearity.
Good timing resolution.
SiPM proved good for photon readout.
SiPM response better than 2 nsec.
In-situ gain calibration by laser
PbF2 crystal purchase in progress

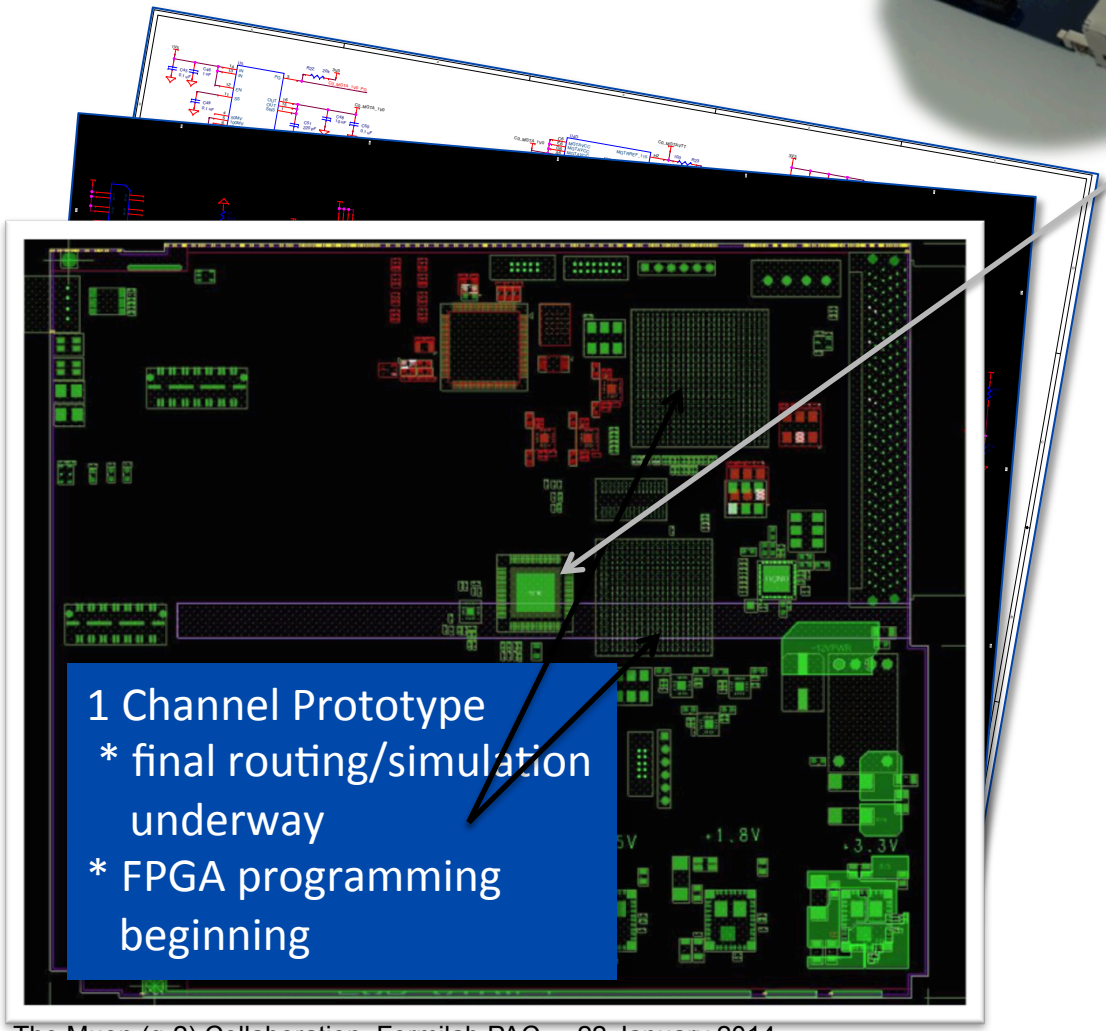


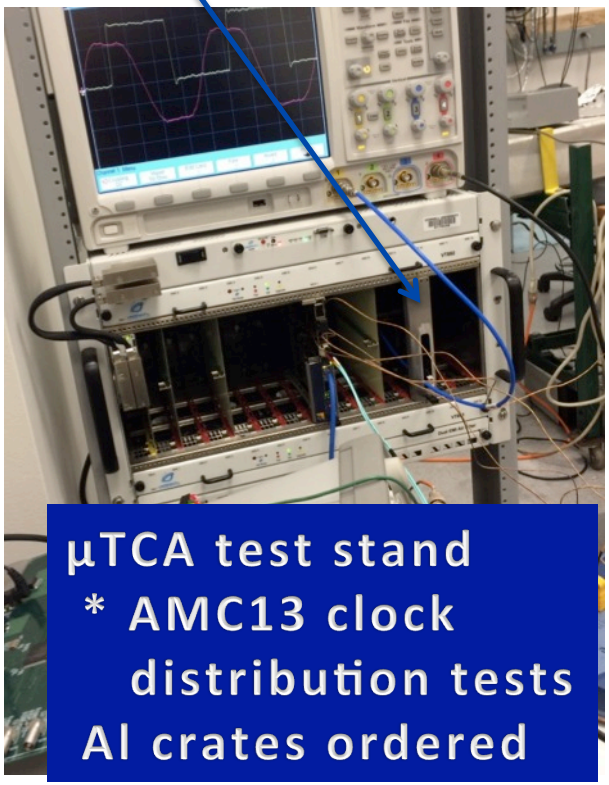
Wave Form Digitizer Highlights

Proto1 board complete
* clock distributions studies
* check mechanicals
* MMC firmware



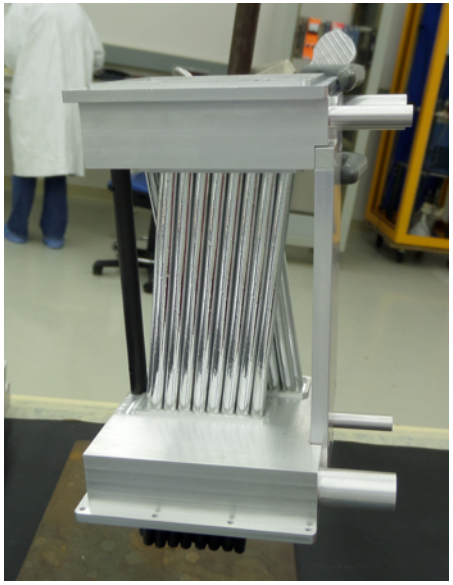




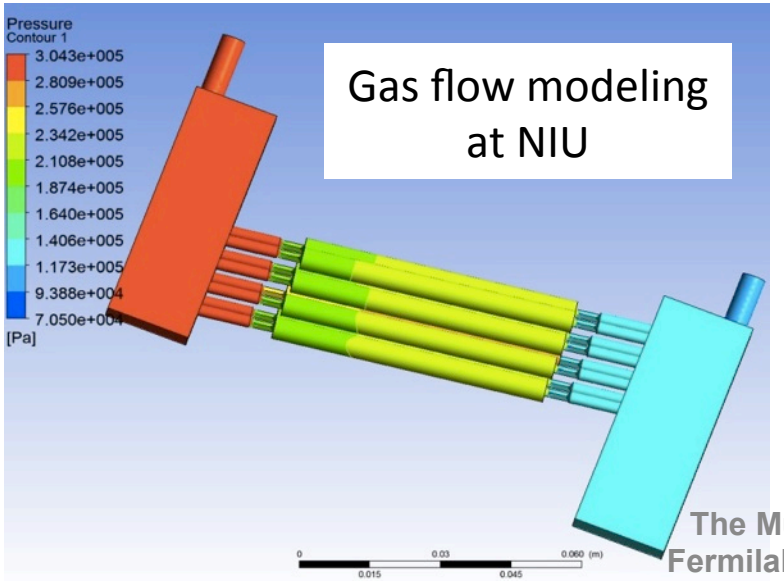


Tracker Hardware

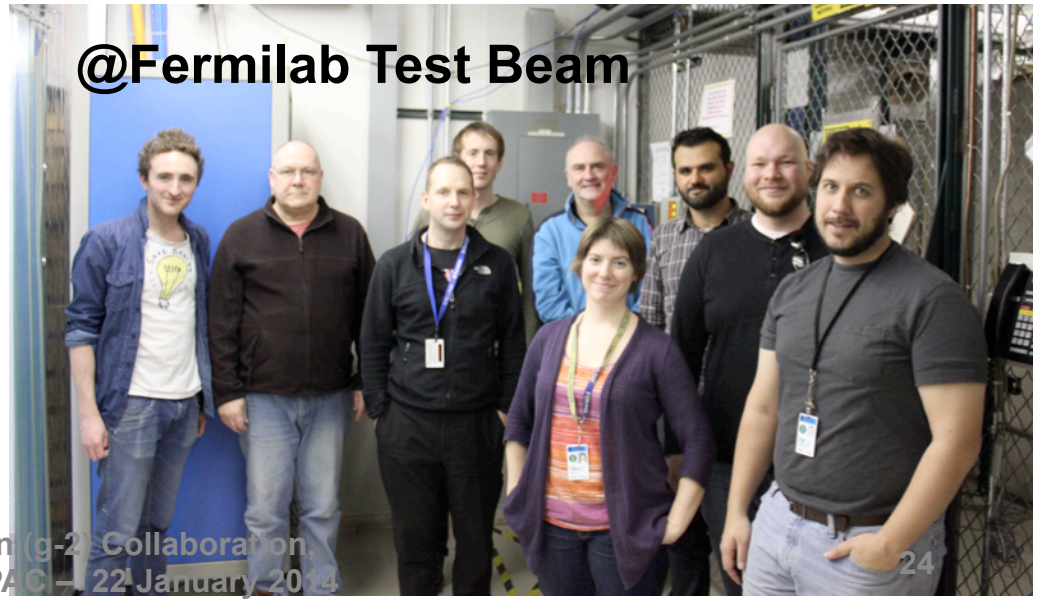
32 channel prototype constructed by Liverpool, NIU, and Fermilab



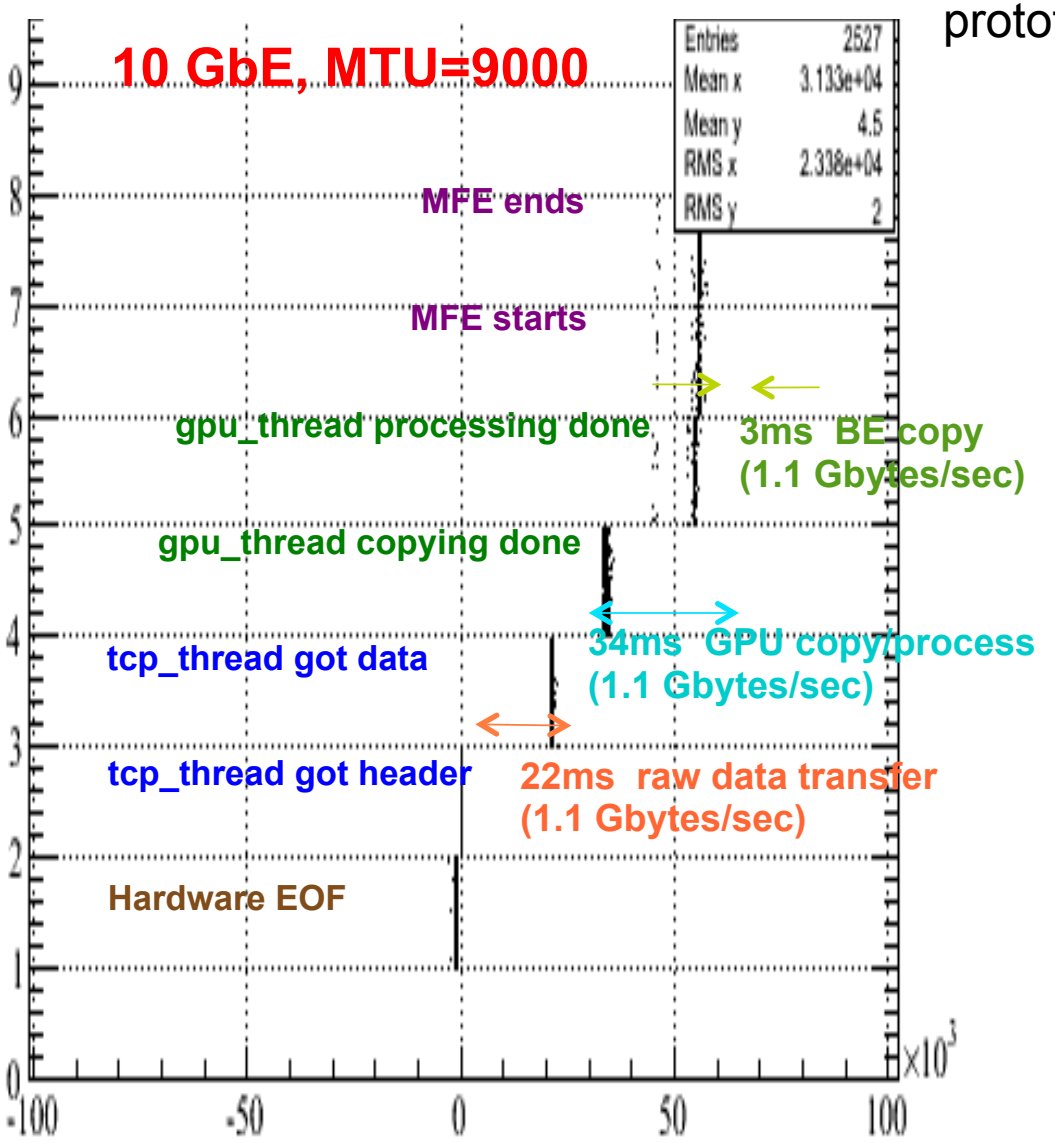
Electronics from Boston



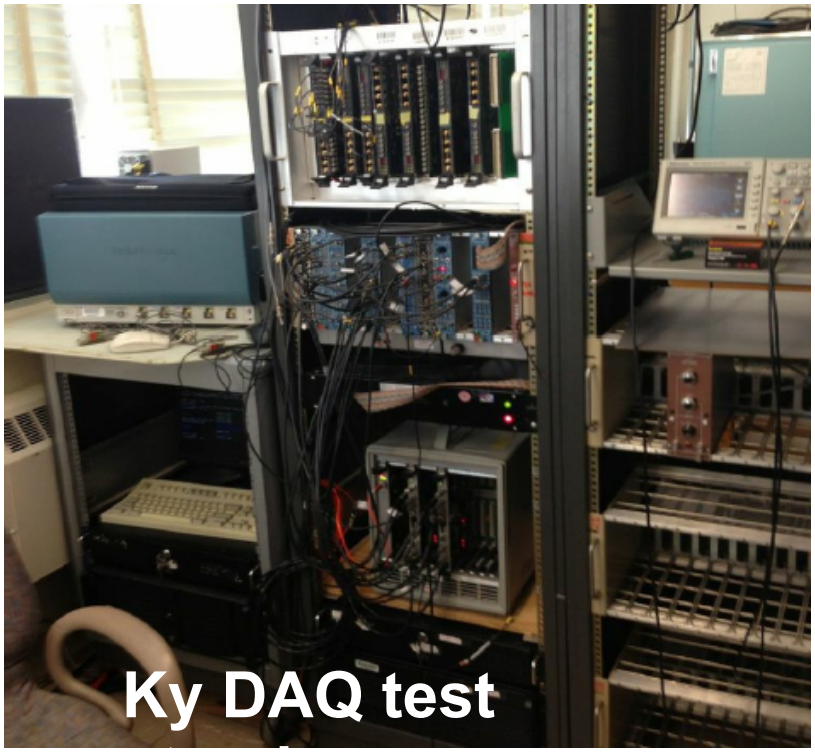
Gas flow modeling at NIU

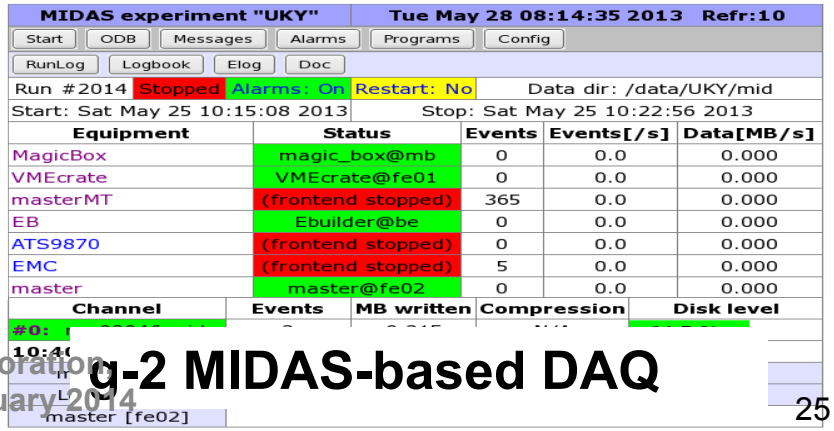


Calo readout timing tests



KY DAQ test stand: 10 GbE readout and GPU-based processing of emulator data, + prototype control synchronization system.





g-2 MIDAS-based DAQ

Building Progress – Beneficial Occupancy 3/14

Stable 2’ 9” (84 cm) thick concrete floor for the storage ring
Temperature control ± 2^{O} F
High bay hall 80’ X 70’ (21.3 m X 24 m) with a 30 T crane
Temperature and floor stability → Much lower systematics on <B> than @ BNL

New Cryogenics Room: beneficial occupancy 1/8

Thanks to Russ Alber and FESS

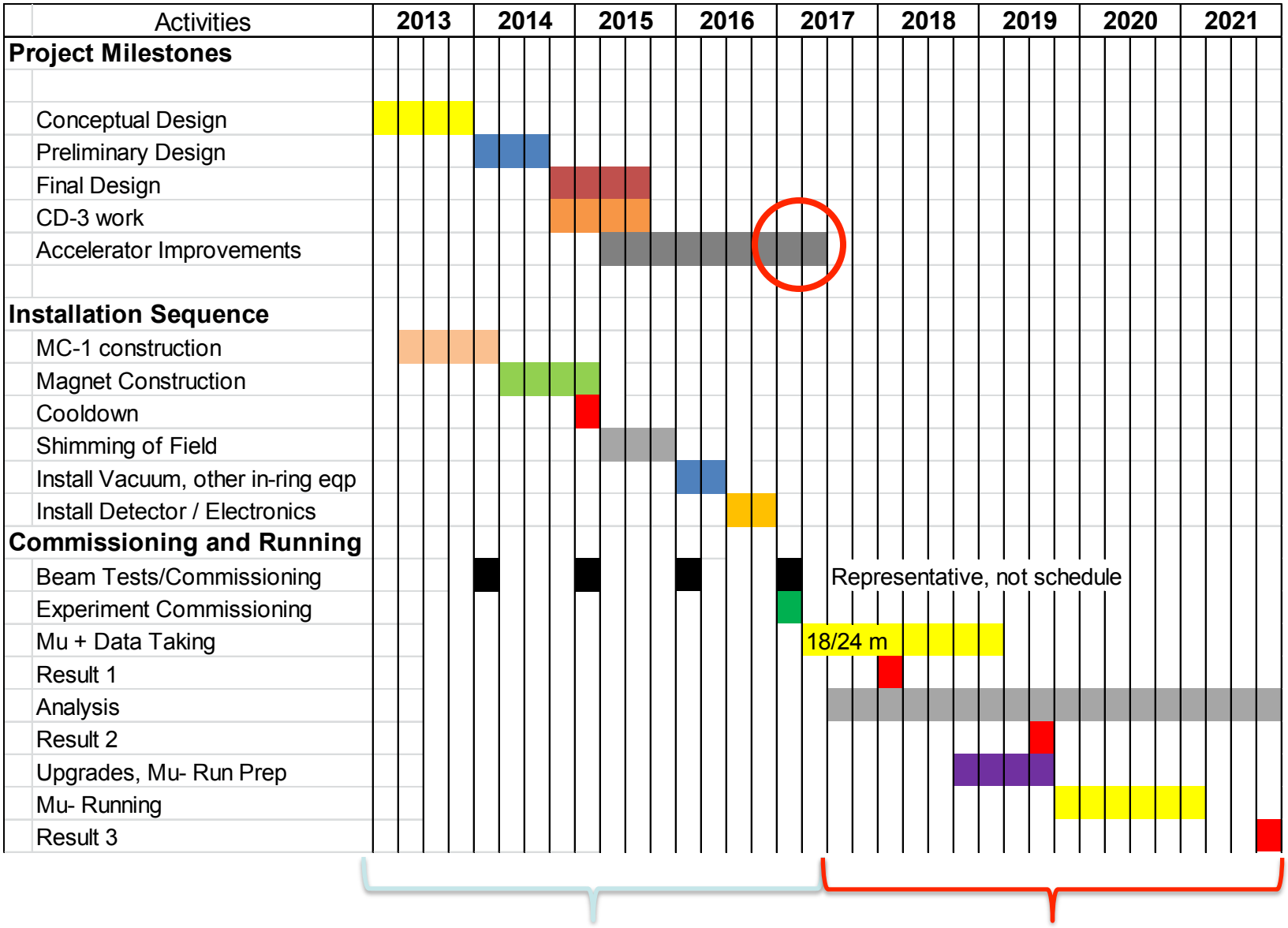
Ring disassembly at BNL

Steel at Fermilab

Reassembly Plans

- Beneficial Occupancy in High Bay in Mid March 2014
- 74F-76F Temperature Control System Commissioning in April 2014
- Practicing Reassembly of Yoke and Pole in ME7 in January 2014.
- New tools being designed to achieve required placement accuracy of ~ 1-5 mil for Poles and Yokes.
- Main Magnet Power Supply System being re-commissioned in D0. already powered successfully; load tests are next.

Timeline (bFY)

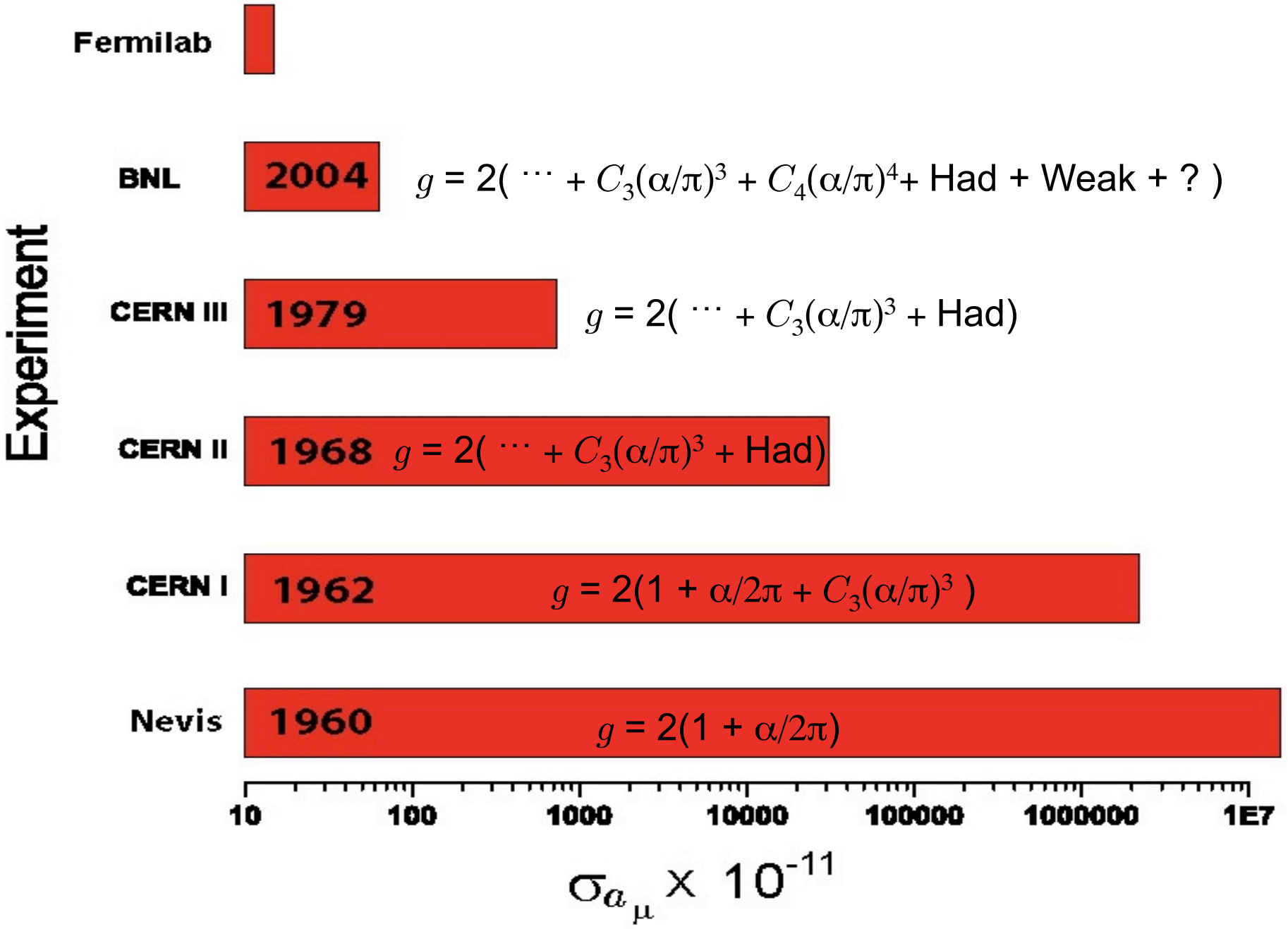


Huge progress since our last PAC presentation

- The E989 Collaboration is now very strong, with a large international component that is making major contributions
- Ring Move almost finished
- Building almost finished
- Prototype detectors being tested in beams at SLAC and Fermilab
- Ring reassembly to begin by March 2014.
- We are working toward CD-2 review in May-June timeframe.

A special thanks to:

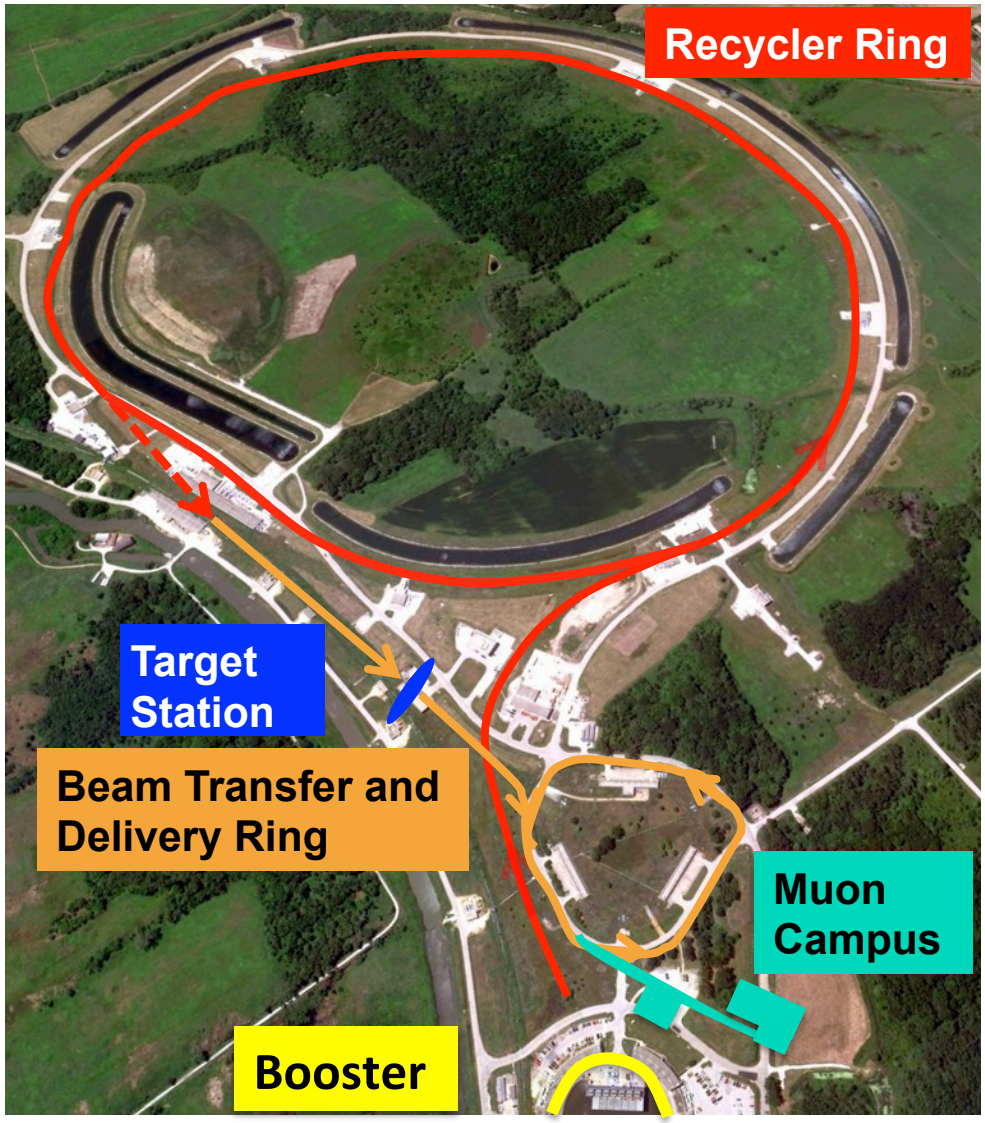
- Lab Management, for significant support throughout the CD-0 CD-1 process, especially to Pier and Nigel for their essential support.
- DOE OHEP for their strong support.
- Russ Alber and the FESS staff for timely construction of the MC1 building.
- Strong DOE-Fermilab-BNL cooperation to move the magnet


Experiment
Fermilab
BNL
2004
$g = 2(\cdots + C_3(\alpha/\pi)^3 + C_4(\alpha/\pi)^4 + \text{Had} + \text{Weak} + ?)$
CERN III
1979
$g = 2(\cdots + C_3(\alpha/\pi)^3 + \text{Had})$
CERN II
1968
$g = 2(\cdots + C_3(\alpha/\pi)^3 + \text{Had})$
CERN I
1962
$g = 2(1 + \alpha/2\pi + C_3(\alpha/\pi)^3)$
Nevis
1960
$g = 2(1 + \alpha/2\pi)$
10
100
1000
10000
100000
1000000
1E7
$\sigma_{a_\mu} \times 10^{-11}$

Extra Slides

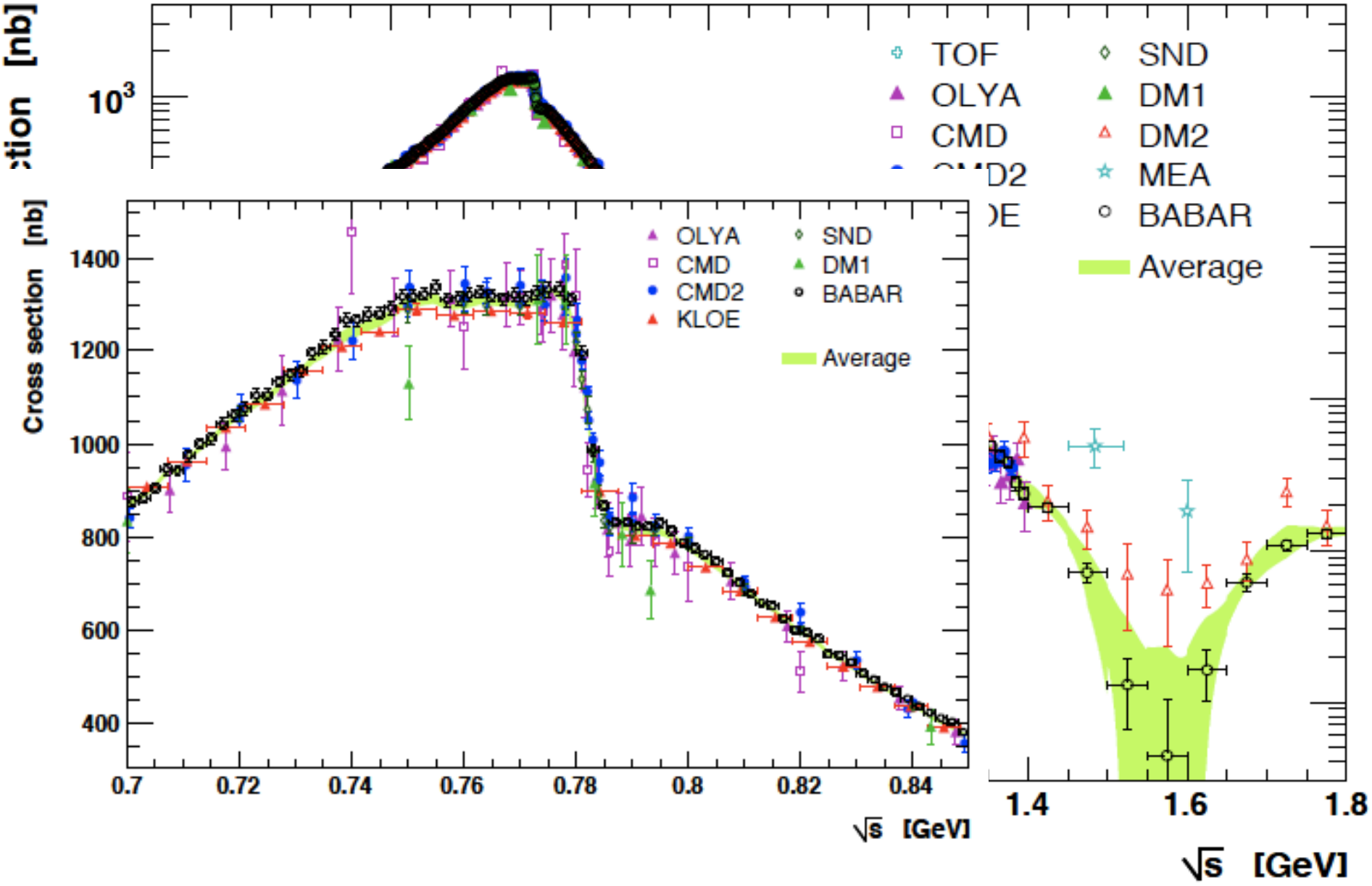
Muon Campus- Project, GPPs, AIPs

- Relocation and re-assembly of storage ring: **Operations**
- Building (Includes cryo plant for Mu2e): **GPP**
- Accelerator modifications common to g-2 and Mu2e: **AIP**
- Beamline construction common to g-2 and Mu2e: **AIP**
- Beamline construction for g-2: **Project**
- Accelerator modifications for g-2: **Project**

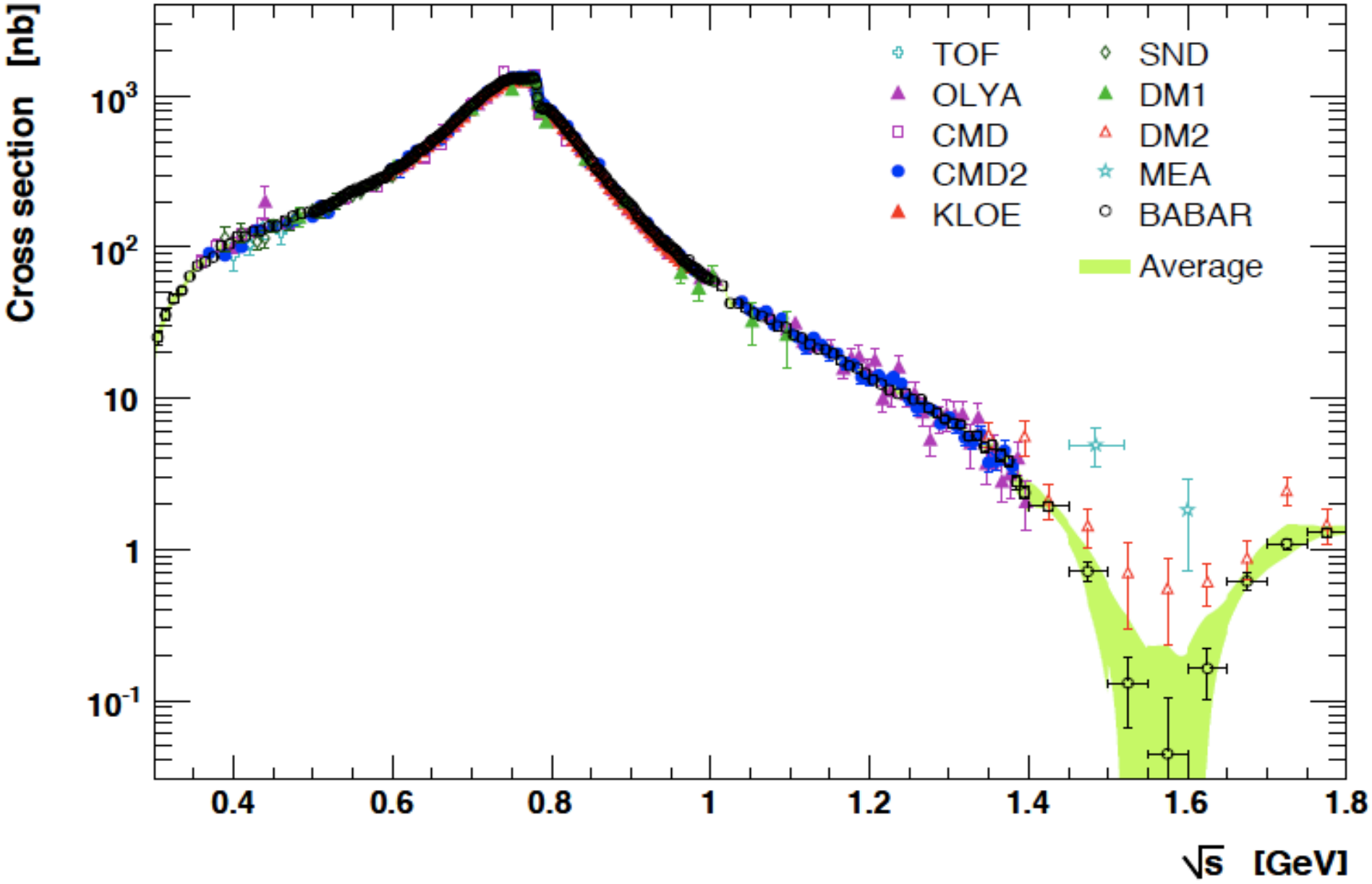


Additional Theory Slides

Existing Cross section measurements for $e^+e^- \to \pi^+\pi^-$



Existing Cross section measurements for $e^+e^- \to \pi^+\pi^-$



A significant world-wide effort to determine a_μ^{Had} continues

The Muon $(g-2)$ Theory Value: Present and Future

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[6]Department of Mathematical Sciences, University of Liverpool, Liverpool, UK
[7]Laboratori Nazionali di Frascati dell'INFN, Frascati, Italy

November 12, 2013

arXiv:1311.2198v1 [hep-ph] 9 Nov 2013

The Standard-Model Value from arXiv:1311.2198

	VALUE ($\times 10^{-11}$) UNITS
QED ($\gamma + \ell$)	$116\,584\,718.951 \pm 0.009 \pm 0.019 \pm 0.007 \pm 0.077_{\alpha}$
HVP(lo) [20]	$6\,923 \pm 42$
HVP(lo) [21]	$6\,949 \pm 43$
HVP(ho) [21]	-98.4 ± 0.7
HLbL "Glasgow Consensus"	105 ± 26
EW	154 ± 1
Total SM [20]	$116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}} (\pm 49_{\text{tot}})$
Total SM [21]	$116\,591\,828 \pm 43_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}} (\pm 50_{\text{tot}})$

$$a_\mu^{exp} = 116\,592\,089(63) \times 10^{-11}\ (0.54\,\text{ppm})$$

$$\Delta a_\mu^{(\text{today})} = (287 \pm 80) \times 10^{-11}$$

$$a_\mu^{EW} = 154(1) \times 10^{-11}$$

Theory Improvements on the Horizon: H-LO

- Lowest order hadronic:
  - Novosibirsk already has an energy-scan data set in hand up to 2 GeV, with the BaBar statistics. Additional data collection soon.
  - BESIII is actively pursing ISR data on 2π, 3π, and 4π channels.
  - The Lattice is becoming relevant and could be competitive with the data driven evaluations by the end of the decade.
- We assume that the experimental cross section errors can be reduced from 0.7% to 0.4% for $E \leq 1$ GeV, and from 6% to 2% for $1 \leq E \leq 2$ GeV.

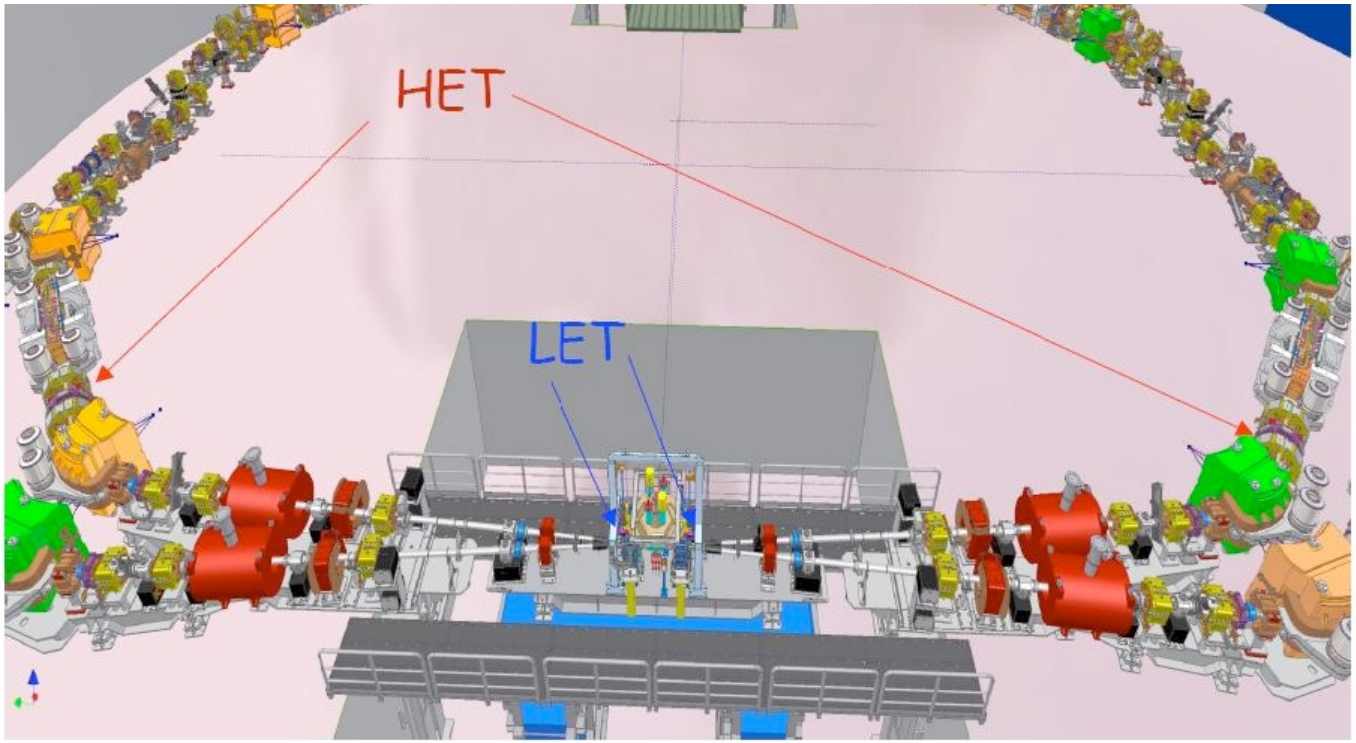
	$\delta(\sigma)/\sigma$ present	δa_μpresent	$\delta(\sigma)/\sigma$ future	δa_μfuture
$\sqrt{s} < 1$ GeV	0.7%	33	0.4%	19
$1 < \sqrt{s} < 2$ GeV	6%	39	2%	13
$\sqrt{s} > 2$ GeV		12		12
total		53		26

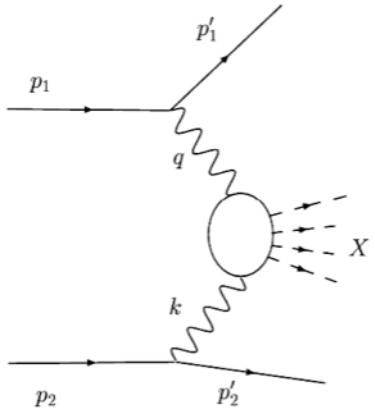
Theory Improvements on the Horizon: HL-b-L

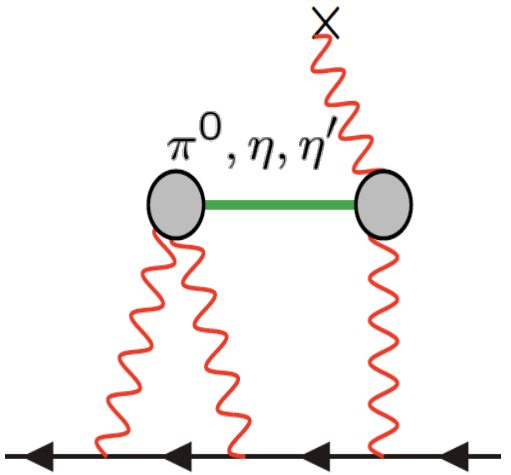
- Hadronic Light-by-light
  - KLOE is preparing a new run focused on $\gamma\gamma^*$ physics using high and low energy taggers for the scattered e^+ and e^-.
  - BESIII $\gamma\gamma^* \rightarrow X$, where $X = \pi^0, \eta, \eta', 2\pi$
- Additional model calculations,
  - e.g. the contribution of scalar, axial vector and tensor mesons have recently been calculated, arXiv:1401.0832v1 [hep-ph], which replaces the estimates used in the "Glasgow Consensus"
  - Lattice: "And while the ultimate goal is to compute the HLbL contribution to 10% accuracy, or better, we emphasize that a lattice calculation with even a solid 30% error would already be very interesting. Such a result, while not guaranteed, is not out of the question during the next 3-5 years."
- We assumed that the HL-b-L "Glasgow Consensus" uncertainty would be agreed upon by all parties, $\pm 25 \times 10^{-11}$

KLOE to measure $\gamma^*\gamma^* \rightarrow$ *hadrons* to constrain HLBL

- Constrain the off-shell amplitudes and remove a significant portion of the theoretical uncertainty on the HLBL







What will the E989 – theory comparison look like?

- With these assumptions of theory improvements, and the E989 error goal of $\pm 16 \times 10^{-11}$ we find the total error on Δ is halved.

Error	[20]	[21]	Future
$\delta a_\mu^{\rm SM}$	49	50	35
$\delta a_\mu^{\rm HLO}$	42	43	26
$\delta a_\mu^{\rm HLbL}$	26	26	25
$\delta(a_\mu^{\rm EXP} - a_\mu^{\rm SM})$	80	80	40

$$\Delta a_\mu^{(\text{today})} = (287 \pm 80) \times 10^{-11}$$